Anisotropic propagation speed of light in a uniform linear motion system relative to earth centered inertial frame

RUYONG WANG[1, *], AND LI ZHAN[2]

[1] *St. Cloud State University, St. Cloud, MN 56301, USA*

[2] *State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*

**Corresponding author: ruwang@stcloudstate.edu*

Abstract

Based on the Global Positioning System (GPS) range measurement equation whose correctness has been fully proven by GPS practices, we found that in an inertial system which is moving relative to the Earth Centered Inertial (ECI) frame, the propagation speed of light is neither constant nor isotropic, but $c' = c - \boldsymbol{v} \cdot \hat{\mathbf{d}}$, where $\boldsymbol{v}$ is the velocity of the system relative to the ECI frame and $\hat{\mathbf{d}}$ is the unit vector of the direction of light propagation. Utilizing an interferometer of two independent ultrastable lasers, a crucial experiment examining this important scientific problem with a low translational speed of the interferometer is proposed; and its comparison with an existing experiment of the generalized Sagnac effect is also presented. Besides, such an interferometer can be utilized to examine another important scientific problem: whether the speed of light is isotropic or not on rotating Earth's surface. Because the vast majority of optical laboratories on the surface of the Earth have high linear velocities of the Earth's rotation, only a small change of the orientation of the interferometer is sufficient.

Keywords: Propagation speed of light; System moving relative to ECI; Theoretical derivation; Crucial experiments; Interferometer of lasers

I. Introduction.

The first principle of Special Relativity is the principle of relativity which states that all physical laws are the same in all systems of coordinates in uniform linear motion [1]. Accordingly, it also means that the propagation speed of light is isotropic in all inertial systems. In 1980, it was indicated that the principle of relativity had not been verified by experiments in a system moving relative to the Earth and a new Michelson-Morley experiment in Space Lab was proposed [2]. Popper thought conducting such an experiment to examine the principle of relativity was a good idea [3]. Although, the experiment has been repeated many times using new technologies with increasing accuracy [4-7], all of them still bear the same feature: the experimental devices are not in uniform linear motion relative to the laboratories on Earth. This means that the principle of relativity of Special Relativity and the isotropy of the speed of light in all inertial systems have not been truly examined by experiments.

In this paper, we analyze the propagation of light between two adjacent points in an inertial system which is moving relative the ECI frame using GPS range measurement equation which is fully proven by GPS practices. We found that the propagation speed of light in that system is neither constant nor isotropic, but $c' = c - \boldsymbol{v} \cdot \hat{\mathbf{d}}$ where $\boldsymbol{v}$ is the linear velocity of system relative to the ECI frame and $\hat{\mathbf{d}}$ is the unit vector of the direction of light propagation; and $\Delta t = d/c + \boldsymbol{v} \cdot \boldsymbol{d}/c^2$, where Δt is the time interval for a light beam to travel the light path d which is in that system.

To examine the findings, we should first mention the key results from previous generalized Sagnac effect experiments [8, 9]: the linear motion causes a first-order propagation time difference between two counter-propagating light beams, $\Delta t = 2vl/c^2$, when the optical path and the direction of motion are in the same line; and more generally $\Delta t = 2\boldsymbol{v} \cdot \boldsymbol{l}/c^2$, when the optical path and the direction of motion have an angle. However, in these experiments only one laser is used and the optical path must be a loop, therefore, they cannot be regarded as a direct examination of the principle of relativity. Then, how do we make an optical path that is not a loop so we can have first-order experiments to examine the principle of relativity? Obviously, we will need to have two independent coherent light sources. With the development of ultrastable lasers nowadays, the linewidth of the laser reaches 5 mHz and the coherence time reaches 200 s [10-12], therefore we can interfere the light beams from two independent lasers [13, 14]. In this way, the experimental arrangement no longer has a loop, making the experiments with two independent lasers in uniform linear motion good candidates for crucially examining the theoretical prediction in this paper.

II. Theoretical derivation for anisotropic propagation speed of light in an inertial system with uniform linear motion relative to ECI frame

Now let us examine the propagation of light in a system in uniform linear motion with respect to the ECI frame.

Accordingly, there are two inertial systems, one is the ECI frame Σ_0, and the other is the Σ_1 moving relative to it with $\boldsymbol{v}$ as shown in the Fig. 1. Fixed in Σ_1 there are two points A and B, and the vector between AB is $\boldsymbol{d}$, which makes an angle ϕ with $\boldsymbol{v}$. Now there is a light beam traveling from A to B. We want to find the time interval Δt for the propagation of this light beam and thus find out what the propagation speed of light is.

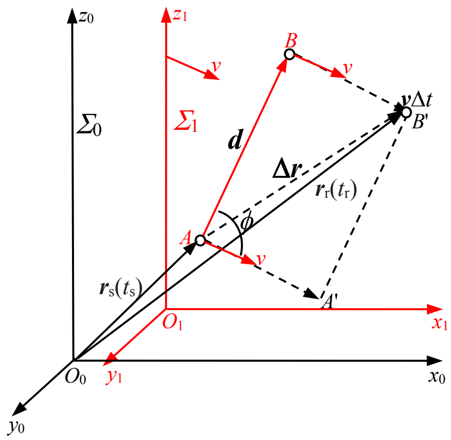


Fig. 1. A light beam propagates from A to B fixed in Σ_1 which is moving relative to Σ_0 with a constant velocity $\boldsymbol{v}$.

The GPS is a timing-ranging system. The operations of GPS are based on the range measurement equation in an Earth-centered inertial system, ECI [15-17]:

$$|\boldsymbol{r}_r(t_r)-\boldsymbol{r}_s(t_s)|=c(t_r-t_s)\,. \tag{1}$$

Here t_s is the time of transmission of the signal from the source, and t_r is the time of reception at the receiver; $\boldsymbol{r}_s(t_s)$ is the position vector of the source at the transmission time, and $\boldsymbol{r}_r(t_r)$ is the position vector of the receiver at the reception time. Highly successful practices of GPS have proved the validity of GPS' range measurement equation. Now we use GPS range measurement equation to analyze the propagation of the light beam.

Because the GPS range measurement equation is utilized in the ECI frame, the problem should be studied in Σ_0. Here the propagation of light from A to B is shown in Fig. 1: the light starts from point A and the vector from the origin O_0 of Σ_0 to point A is $\boldsymbol{r}_s(t_s)$. While the light reaches the receiving point after a time interval Δt, since B is moving in Σ_0, B arrived at the point B' and $BB'=v\Delta t$, and the vector from the origin O_0 to B' is $\boldsymbol{r}_r(t_r)$. Apparently (t_r-t_s) in the GPS range measurement equation is the Δt we are searching for.

We have in Fig. 1 a triangle of vectors, $\boldsymbol{d}$, $\boldsymbol{v}\Delta t$ and $\Delta\boldsymbol{r}$, and $\Delta\boldsymbol{r}=|\boldsymbol{r}_r(t_r)-\boldsymbol{r}_s(t_s)|$. The relationship among the vectors $\boldsymbol{d}$, $\boldsymbol{v}\Delta t$ and $\Delta\boldsymbol{r}$ gives us

$$|\Delta\boldsymbol{r}|^2=d^2+(v\Delta t)^2+2\boldsymbol{d}\cdot\boldsymbol{v}\Delta t\,. \tag{2}$$

Using the GPS range measurement equation (1), we have $|\Delta\boldsymbol{r}|=c\Delta t$ **.**

Thus we have $c^2\Delta t^2=d^2+v^2\Delta t^2+2\boldsymbol{d}\cdot\boldsymbol{v}\Delta t$. Because of $v^2<<c^2$, then,

$$\Delta t^2-(2\boldsymbol{d}\cdot\boldsymbol{v}/c^2)\Delta t-d^2/c^2=0\,. \tag{3}$$

Solving this equation for Δt, we have

$$\Delta t=d/c+\boldsymbol{v}\cdot\boldsymbol{d}/c^2\,. \tag{4}$$

Δt is the time interval of the light beam to travel the path d.

Now let us calculate the speed of light of this beam c' in inertial system Σ_1, namely, c'=(distance of propagation)/(time interval)= $d/\Delta t$. Thus we have

$$c'=d/\Delta t=d/(d/c+\boldsymbol{v}\cdot\boldsymbol{d}/c^2)=c^2/(c+\boldsymbol{v}\cdot\hat{\mathbf{d}})=c^2(c-\boldsymbol{v}\cdot\hat{\mathbf{d}})/(c-\boldsymbol{v}\cdot\hat{\mathbf{d}})(c+\boldsymbol{v}\cdot\hat{\mathbf{d}})\approx c-\boldsymbol{v}\cdot\hat{\mathbf{d}}\,, \tag{5}$$

neglecting the quantities of second and higher orders of (v/c). There, $\boldsymbol{v}$ is the constant velocity of the system relative to the ECI frame and $\hat{\mathbf{d}}$ is the unit vector of the direction of light propagation. Alternatively, we can express it as $c' = c - v\cos\phi$.

The difference between this result $c'/c = 1 - v\cos\phi/c$ and general belief that the propagation speed of light is isotropic in any inertial system, i.e., $c'/c \equiv 1$, is a first-order quantity, $v\cos\phi/c$. Therefore, it is clear that the difference between the two would not disappear by considering Lorentz contraction and relativistic time dilation, the second-order quantities [$\propto (v/c)^2$].

III. The propagation speed of light in a system with uniform linear motion on rotating Earth's surface.

The vast majority of us live on the Earth surface, and the vast majority of events related to the propagation speed of light occur on the surface of the rotating Earth. The vast majority of experiments related to the propagation speed of light are conducted on the surface of the rotating Earth. So, we are now further investigating the problem of the propagation speed of light in a system with uniform linear motion on the Earth **s**urface. Here we would first mention a previous work of ours [18], which states that the propagation speed of light on rotating Earth's surface is neither a constant nor isotropic, but $c' = c - \boldsymbol{v}_{rE}\cdot\hat{\mathbf{d}}$, where $\boldsymbol{v}_{rE}$ is the local linear velocity of Earth's rotation, and $\hat{\mathbf{d}}$ is the unit vector of the light propagation's direction

Based on that, we now examine the propagation of light in the following scenario (Fig. 2): where there is an ECI frame Σ_0, and system Σ_1 is in an uniform linear motion $\boldsymbol{v}$ with respect to a place on the surface of the rotating Earth. Fixed in Σ_1 there are two points A and B, and the vector between A and B is $\boldsymbol{d}$. There is a light beam traveling from A to B. We want to find the time interval Δt for the propagation of this light beam.

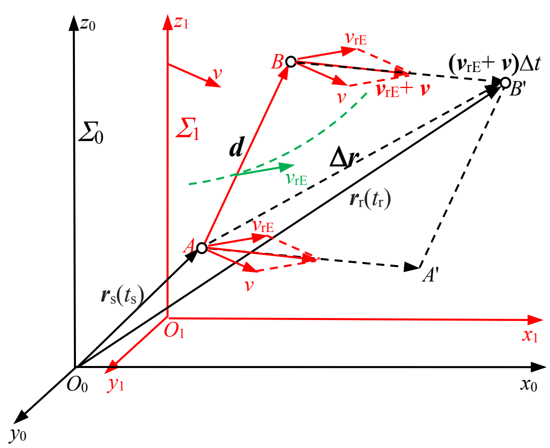


Fig. 2. A light beam propagates from A to B fixed in Σ_1 which is moving with a constant velocity $\boldsymbol{v}$ on the surface of rotating Earth.

Unlike the scenario in Fig. 1, here when a light beam is emitted from A, A and B have two simultaneous motions, one is a uniform linear motion with speed $\boldsymbol{v}$, and the other is motion caused by the rotation of the Earth with speed $\boldsymbol{v}_{rE}$. That is to say, compared with the situation in the previous section, vector $\boldsymbol{v}$ there is replaced by the sum of two vectors $\boldsymbol{v}+\boldsymbol{v}_{rE}$ in this section.

We can solve the problem step by step as we did in the previous section, however due to the similarity between these two scenarios, we can also directly modify the results in the previous section to get the results for the present scenario. The vector triangle now is $\boldsymbol{d}$, $(\boldsymbol{v}+\boldsymbol{v}_{rE})\Delta t$ and $\Delta\boldsymbol{r}$.

Using GPS range measurement equation in this case, we have the result of time interval of light propagation: $\Delta t = d/c + (\boldsymbol{v}+\boldsymbol{v}_{rE})\cdot\boldsymbol{d}/c^2$, and the speed of light is $c' = c - (\boldsymbol{v}+\boldsymbol{v}_{rE})\cdot\hat{\mathbf{d}}$.

Obviously, if there is no uniform motion $\boldsymbol{v}$, then this result becomes the result of the propagation speed of light on rotating Earth' surface, $c' = c - \boldsymbol{v}_{rE}\cdot\hat{\mathbf{d}}$; and if there is no effect caused by the rotation of the Earth, then this result becomes what we have in the previous section, $c' = c - \boldsymbol{v}\cdot\hat{\mathbf{d}}$ **.**

IV. Crucial interferometric experiments with two independent ultrastable lasers.

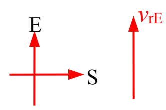
1. Examining the anisotropic propagation speed of light in a system with uniform linear motion.

As previously mentioned, the experimental apparatus with two independent lasers in uniform linear motion can be used here for examining the theoretical prediction.

First, we want to conduct the experiments to examine the anisotropic propagation speed of light in a system with uniform linear motion. However, in general, experiments are always carried out in laboratories on the surface of the Earth, and therefore we must deal with the effect of the Earth's rotation mentioned in the previous section and exclude its effect. For this reason, the direction of propagation of light should be perpendicular to the direction of the Earth's rotation, i.e. $\hat{\mathbf{d}} \perp \boldsymbol{v}_{rE}$. That is, the direction of propagation of light is north-south.

Fig. 3-1 shows an interferometric experiment using two independent ultrastable lasers, and the two lasers and other devices are mounted on a movable optical platform with air bearings or magnetic levitation.

Now let us investigate the change that would be found at the detector when the platform makes an southward motion then a northward motion. Noticeably, this is the change which happens due to the motion in the optical path of length L from the mirror to the beam splitter (*i.e.*, the difference between the two optical paths in the same direction as the motion). The two optical paths perpendicular to the direction of motion will not generate changes at the detector, because firstly, they are very short; secondly, they can be the same length L_1; and thirdly, their light propagation is not affected by the motion.



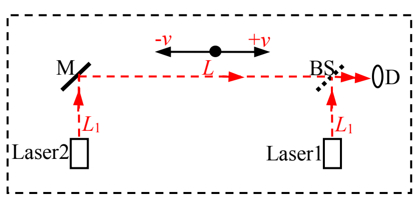


Fig. 3-1. Light propagation experiment with two independent lasers and a movable platform. M - Mirror, BS - Beam Splitter, D - Detector.

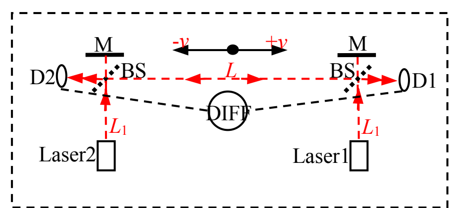


Fig. 3-2. Light propagation experiment with two independent lasers and a movable platform. The optically stable configuration with two detectors. M - Mirror, BS - Beam Splitter, D - Detector, DIFF - Differentiator.

Thus when the optical platform is stationary, the propagation time difference of the two independent coherent beams obtained from the detector is $\Delta t_0 = L/c$.

When the optical platform is moving with a uniform speed v to the south, according to the analysis in the section II, we have $c' = c - v$, and $\Delta t_1 = L/c' = L/c + vL/c^2$.

That means the change found on the detector due to the motion southward is $\Delta t_1 - \Delta t_0 = vL/c^2$. And when the whole platform moves north with v, we have $\Delta t_2 = L/c - vL/c^2$. Therefore, the propagation time difference between the two states of motion is $\Delta t = \Delta t_1 - \Delta t_2 = 2vL/c^2$.

An optically stable configuration is shown in the Fig. 3-2, where there are two detectors. Detector D1 measures the propagation time difference in the southward light paths, while D2 measures that in the northward light paths, and then we can further find the difference between the two measurements with a differentiator working wired or wireless. The process of finding the difference between the two measured quantities can evidently eliminate the influence of vibrations in the light path and the influence of the propagating medium in these two measurements, because those two influences are the same in both directions, leaving only the difference caused by the motion of the light path which we are interested in. Therefore, this configuration inevitably ends up with a very stable experimental result, as seen in the generalized Sagnac experiment for linear motion.

Now when the platform moves southward, compared with the stationary status, on D1, we have $\Delta t_1 = vL/c^2$ and on D2, $\Delta t_2 = -vL/c^2$. That means $\Delta t_1 - \Delta t_2 = 2vL/c^2$. And for moving northward, $\Delta t'_1 - \Delta t'_2 = -2vL/c^2$.

Finally, we have

$$(\Delta t_1 - \Delta t_2) - (\Delta t'_1 - \Delta t'_2) = 4vL/c^2 , \tag{6}$$

and as mentioned before, the influences of the vibration and the propagation medium will be automatically cancelled.

If the time difference is measured as the shift of the interference fringes, it is

$$(\Delta f_1 - \Delta f_2) - (\Delta f'_1 - \Delta f'_2) = 4vL/c\lambda , \tag{7}$$

and the differentiator used is a fringe shift differentiator. Its corresponding phase shift is

$$(\Delta\phi_1 - \Delta\phi_2) - (\Delta\phi'_1 - \Delta\phi'_2) = 8\pi vL/c\lambda , \tag{8}$$

and the differentiator used is a phase shift differentiator.

They are first-order effects, therefore, compared to second-order Michelson-Morley experiments, now the required speed of the motion is considerably low. For example, if we choose v = 0.1 m/s, and L = 3 m, λ = 1.5 μm, according to eq. (8) we have $(\Delta\phi_1 - \Delta\phi_2) - (\Delta\phi'_1 - \Delta\phi'_2) = 8\pi vL/c\lambda = 1.68\cdot 10^{-2}$ rad.

For an optically stable interferometer, such an interference fringe shift is not difficult to detect. And as comparisons, Lorentz contraction and relativistic time dilation are the second-order effects.

Now let us compare the experimental configuration in Fig. 3-2 with the configuration of the fiber optic parallelogram in experiments of Generalized Sagnac Effect [9], and find what they reveal to us. In Fig. 4 we show two configurations together. The similarities between the two are that both of their top optical paths are in motion and it is their movements that generate the phase differences across the optical paths; and that both of their side paths are short and do not contribute any phase difference of the optical path. The only difference between the two is that the stationary bottom side of the fiber optic parallelogram is a part of the entire loop, whereas the present experimental configuration with two independent lasers does not have an optical path at the bottom side, avoiding a loop structure.

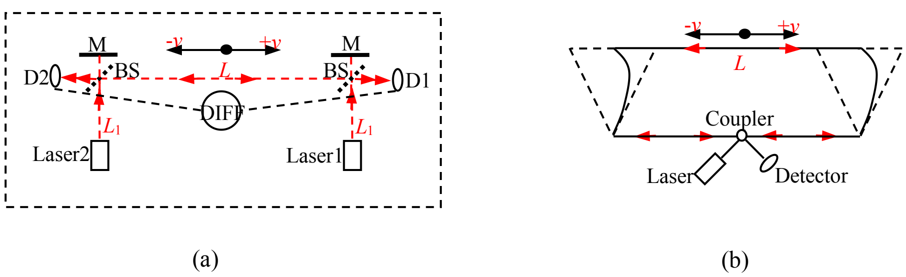


Fig. 4. Comparison between (a) the configuration of current experiment in Fig. 3-2, and (b) the configuration of fiber optic parallelogram in experiments of Generalized Sagnac Effect.

In the fiber optic parallelogram experiment, there is a phase difference $\Delta\phi = 4\pi vL/c\lambda$ when the top path is moving to one side at speed v, and a phase difference $\Delta\phi' = -4\pi vL/c\lambda$ when the top path is moving to the other side at v; therefore the difference between the two is $\Delta\phi - \Delta\phi' = 8\pi vL/c\lambda$. Thus we can expect that the experiment in Fig. 3-2 should yield the result described above, i.e., $(\Delta\phi_1 - \Delta\phi_2) - (\Delta\phi'_1 - \Delta\phi'_2) = 8\pi vL/c\lambda$.

The comparison above highlights once again the importance of utilizing two independent ultrastable lasers in the interferometric experiment, indeed, they eliminate the loop structure of the optical path, thus making this interferometric experiment a crucial one.

2. Examining the anisotropy of the propagation speed of light on the rotating Earth's surface.

In [18] there is a crucial experiment examining the anisotropy of the propagation speed of light on the rotating Earth's surface using stable pulsed laser and ultrafast imaging techniques to compare the spacing of the pulses in different directions. Now we designed the experiment using an interferometer with two independent lasers for this purpose. And we can find that comparing with previous section, using such an interferometer here has advantages. First, examining the speeds of light in different directions means requiring a change of the orientation of the optical platform, which is much easier than a change of the translational speed of the optical platform. And second, the local linear velocities of the Earth's rotation at most optical laboratories are higher than 300 m/s, so that any small change in the orientation of the optical platform will cause a big change of local propagation speed of light. Figure 5 shows such experimental setups.

For Fig.5-1a, there is no translational speed v, and $\boldsymbol{v}_{rE}\cdot\hat{\mathbf{d}}$ = 0, therefore, we have $\Delta t_0 = L/c$.

For Fig. 5-1b, we have $c' = c - \boldsymbol{v}_{rE}\cdot\hat{\mathbf{d}} = c - v_{rE}\cos\theta$, and

$\Delta t_1 = L/c' = L/(c - v_{rE}\cos\theta) \approx (Lc + Lv_{rE}\cos\theta)/c^2 = L/c + (Lv_{rE}\cos\theta/c^2)$.

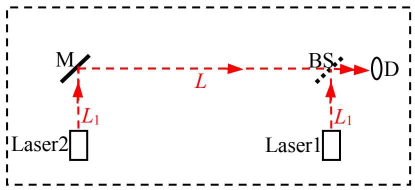
Therefore, on the detector, we can find:

$$\Delta t_1 - \Delta t_0 = Lv_{rE}\cos\theta/c^2 \ . \qquad (9)$$

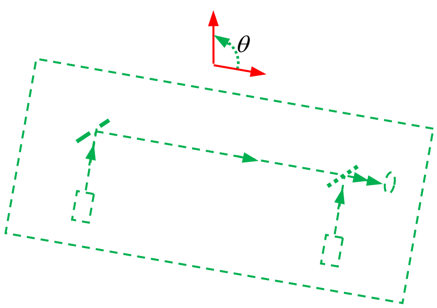
Or, we have:

$$\Delta\phi_1 - \Delta\phi_0 = 2\pi Lv_{rE}\cos\theta/c\lambda \ . \qquad (10)$$

If v_{rE} = 300 m/s, and L = 3 m, λ = 1.5 μm and $\theta = 100$ degrees, according to eq. (10) we have $\Delta\phi_1 - \Delta\phi_0 = -2.18$ rad.

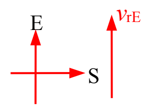


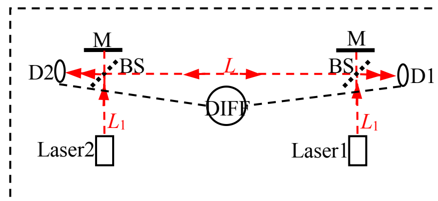
(a)



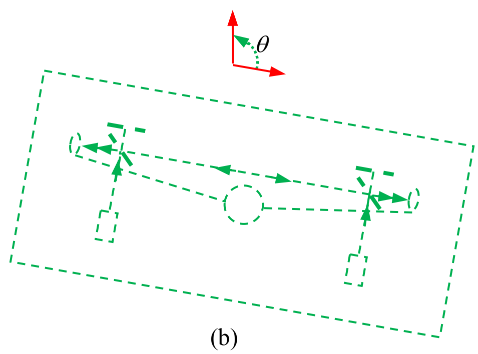
(b)

Fig. 5-1. Light propagation experiment with two independent lasers and a change of the orientation of the optical platform. M - Mirror, BS - Beam Splitter, D - Detector.





(a)



(b)

Fig. 5-2. Light propagation experiment with two independent lasers and a change of the orientation of the optical platform. The optically stable configuration with two detectors. M - Mirror, BS - Beam Splitter, D - Detector, DIFF - Differentiator.

Fig. 5-2 shows an optically stable configuration. By the same token, if we conduct the experiment in the Fig. 5-2, we will have $(\Delta\phi_1 - \Delta\phi_2) - (\Delta\phi'_1 - \Delta\phi'_2) = 4\pi Lv_{rE}\cos\theta/c\lambda = -4.36$ rad.

This confirms what we said above that any small change in the orientation of the optical platform will cause a big change of local propagation speed of light. So in actuality, to conduct this experiment, we just need to change the angle much less.

V. Conclusions.

According to the principle of relativity, the propagation speed of light is constant and isotropic in all inertial systems. Utilizing the GPS range measurement equation, it is found that in an inertial system that is moving with respect to the ECI frame, the propagation velocity of light is neither constant nor isotropic, but $c' = c - \boldsymbol{v}\cdot\hat{\mathbf{d}}$, where $\boldsymbol{v}$ is the velocity of the system relative to the ECI frame and $\hat{\mathbf{d}}$ is the unit vector in the light propagation direction. With an interferometer consisting of two independent ultrastable lasers, a crucial experiment to examine this important scientific problem is proposed. Besides, a comparison of the crucial experiment's configuration with the configuration of completed fiber optic parallelogram experiment of generalized Sagnac effect is also presented. The main similarity between the two is that both of their top optical paths are in motion and their movements generate the phase differences across the optical paths. And therefore from the result of fiber optic parallelogram experiment, we can expect the proposed crucial experiment would show the result theoretically deduced, $(\Delta\phi_1 - \Delta\phi_2) - (\Delta\phi'_1 - \Delta\phi'_2) = 8\pi vL/c\lambda$.

Additionally, a previous research has indicated that the propagation speed of light on rotating Earth's surface is $c' = c - \boldsymbol{v}_{rE}\cdot\hat{\mathbf{d}}$, where $\boldsymbol{v}_{rE}$ is the local linear velocity of Earth's rotation, and $\hat{\mathbf{d}}$ is the unit vector of the light propagation's direction. The

interferometer of two independent ultrastable lasers can also be utilized to study this important problem. As the vast majority of optical laboratories on the ground have high linear velocities of Earth's rotation, the interferometer can be utilized here especially efficiently; and only a small change of the orientation of the interferometer is sufficient.

References

[1] A. Einstein, "Zur Elektrodynamik bewegter Körper", Annalen der Physik, **17**, 891 (1905).

[2] R. Wang, Z. Chen, X. Dong, "Has the Relativity Principle in the Special Theory of Relativity Been Fully Verified by Experiments?", Phys. Lett. **75A**, 176 (1980) .

[3] K. Popper, private communication, Karl Popper Archive, 1981.

[4] H. Müller, S. Herrmann, C. Braxmaier, S. Schiller, and A. Peters, "Modern Michelson-Morley experiment using cryogenic optical resonators," Phys. Rev. Lett. **91**, 020401 (2003).

[5] P. Stanwix, M. Tobar, P. Wolf, M. Susli, C. Ivanov, J. Winterflood, and F. Kann, "Test of Lorentz invariance in electrodynamics using rotating cryogenic sapphire microwave oscillators," Phys. Rev. Lett. **95**, 040404 (2005).

[6] C. Eisele, A. Nevsky, S. Schillerv, "Laboratory test of the isotropy of light propagation at the 10^{-17} level," Phys. Rev. Lett. **103**, 090401 (2009).

[7] Herrmann, A. Senger, K. Möhle, M. Nagel, E. Kovalchuk, and A. Peters, "Rotating optical cavity experiment testing Lorentz invariance at the 10^{-17} level," Phys. Rev. D. **80**, 105011 (2009).

[8] R. Wang, Y. Zheng, A. Yao, D. Langley, "Modified Sagnac Experiment for Measuring Travel-Time Difference between Counter-Propagating Light Beams in a Uniformly Moving Fiber", Phys. Lett. A, **312**, 7 (2003).

[9] R. Wang, Y. Zheng, A. Yao, "Generalized Sagnac Effect", Phys. Rev. Lett. **93**, 143901 (2004).

[10] Matei D., *et al*., "1.5 μ m Lasers with Sub-10 mHz Linewidth", Phys. Rev. Lett., **118**, 263202 (2017).

[11] Kessler, T., et al. "A sub-40-mHz-linewidth laser based on a silicon single-crystal optical cavity." Nature Photon., **6**, 687 (2012).

[12] Schioppo, M., *et al.* "Comparing ultrastable lasers at 7×10^{-17} fractional frequency instability through a 2220 km optical fibre network." Nature Commun., **13**, 212 (2022).

[13] Magyar, G., Mandel, L. "Interference Fringes Produced by Superposition of Two Independent Maser Light Beams," Nature **198**, 255 (1963).

[14] Kawalec T. and Sowa P., "Observation of two truly independent laser interference made easy" Eur. J. Phys., **42**, 055305 (2021).

[15] ICD-GPS-200C, "Navstar GPS Space Segment/Navigation User Interfaces", Revision 4, 12 April 2000.

[16] Ashby, "Relativity in the Future of Engineering," IEEE Trans. Inst. and Meas. **43**(4), 505-514 (1994).

[17] B. Parkinson, J. Spilker, Global Positioning System: Theory and Applications, Vol. I (AIAA Inc.1996).

[18] R. Wang, L. Zhan, "Anisotropic propagation speed of light on rotating Earth's surface - theoretical derivation, implications for definition of meter, and crucial experiment" chinaXiv:202307.00036.